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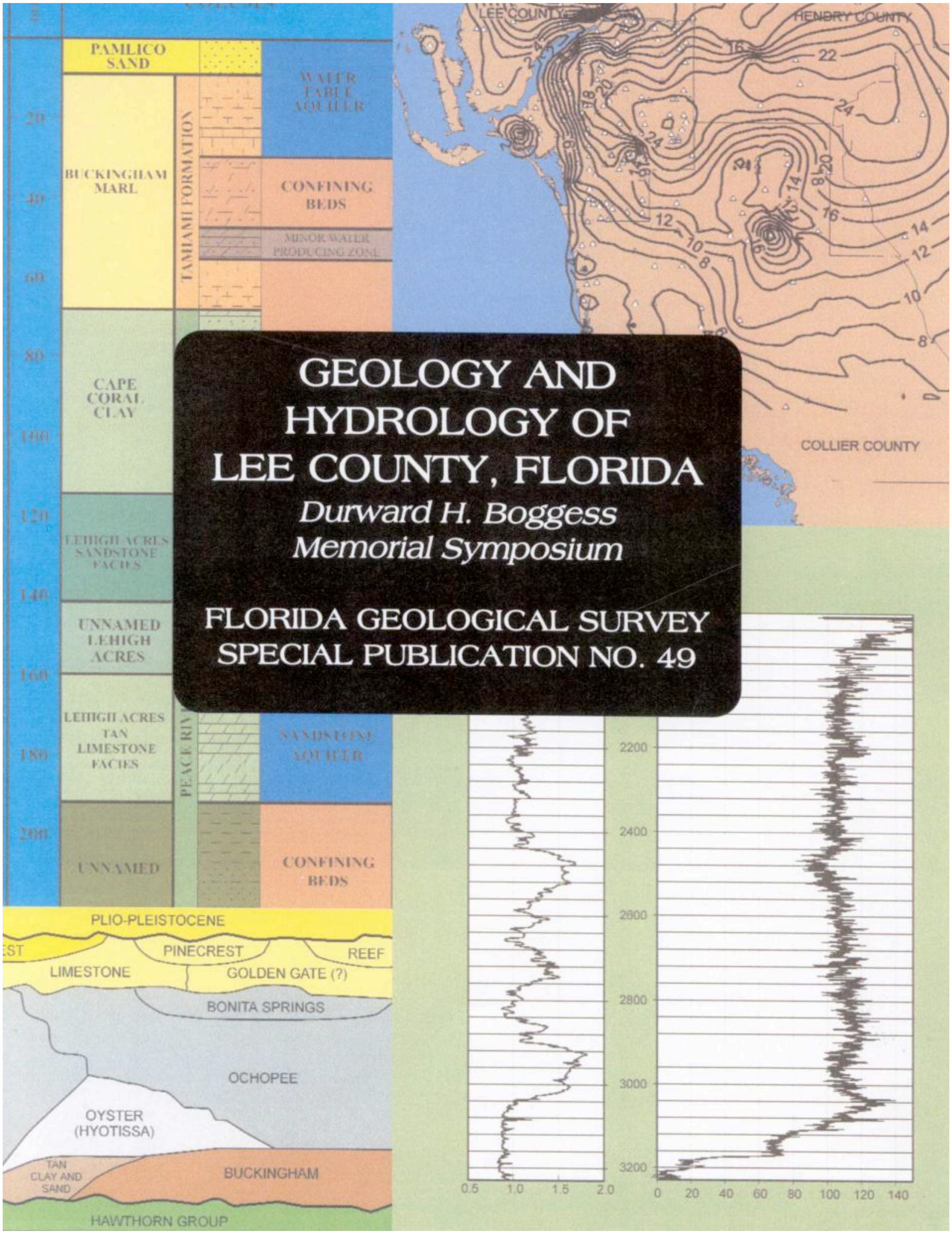

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SEQUENCE STRATIGRAPHY OF A SOUTH FLORIDA CARBONATE RAMP AND BOUNDING SILICICLASTICS (LATE MIOCENE-PLIOCENE)

Kevin J. Cunningham[1], David Bukry[2], Tokiyuki Sato[3], John A. Barron[2], Laura A. Guertin[4], and Ronald S. Reese[1]

1. U.S. Geological Survey. 9100 N.W. 36th Street. Suite 107. Miami. FL 33178
2. U.S. Geological Survey. 345 Middlefield Road. Menlo Park. CA 94025
3. Institute of Applied Earth Sciences. Mining College. Akita University. Tegata-Gakuencho 1-1. Akita, 010, Japan
4. Mary Washington College. Fredericksburg. VA 22401

ABSTRACT

In southern peninsular Florida, a late-early to early-late Pliocene carbonate ramp (Ochopee Limestone Member of the Tamiami Formation) is sandwiched between underlying marine siliciclastics of the late Miocene to early Pliocene Peace River Formation and an overlying late Pliocene unnamed sand. At least three depositional sequences (DS1 , DS2, and DS3), of which two contain condensed sections, are recognized in the Peace River Formation; an additional depositional sequence (DS4) is proposed to include the Ochopee Limestone.

Established chronologies and new biostratigraphic results indicate that the Tortonian and Zanclean ages bracket the Peace River Formation. Depositional sequence 1 (DS1) prograded across the present-day peninsular portion of the Florida Platform during the Tortonian age and laps out near the southern margin of the peninsula. During the latest Tortonian and Messinian ages, progradation of DS2 overstepped the southern lap out of DS1 and extended at least as far as the Florida Keys. Deposition of DS2 ended, at the latest, near the Miocene-Pliocene boundary. Siliciclastic supply was reduced during early Pliocene deposition of DS3, which is absent in southernmost peninsular Florida. This reduction in supply of siliciclastics was followed by aggradational accumulation of heterozoan temperate carbonate sediments on a widespread carbonate ramp that includes the Ochopee Limestone. The Ochopee Limestone was deposited during eustatic cycle TB3.6 and ended in the late Pliocene with basinward lap out near the southern margin of the Florida peninsula. The Ochopee Limestone ramp was buried with a late Pliocene resumption of southward influx of siliciclastics (unnamed sand and Long Key Formation) that extended south beyond the middle and upper Florida Keys.

INTRODUCTION

Until the early 1990'5, stratigraphic investigations of Miocene-Pliocene siliciclastics and carbonates beneath southern Florida focused on lithostratigraphy (Peck et al., 1979; Wedderburn et al., 1982; Peacock, 1983; Missimer, 1984; Knapp et al., 1986; Scott, 1988; Smith and Adams, 1988; Missimer, 1992). Recently, sequence stratigraphy has contributed to conceptualizing a more accurate spatial and temporal framework of the Miocene-Pliocene stratigraphic framework of southern Florida (Evans and Hine, 1991; Warzeski et al., 1996; Missimer, 1997; Cunningham et al., 1998; Guertin et al., 1999; Missimer, 1999; Guertin et al., 2000). This developing sequence-stratigraphic framework for southern Florida is the result of integrating lithostratigraphy, micropaleontology, magnetostratigraphy, strontium-isotope chemostratigraphy, and seismic stratigraphy along with delineating unconformities that bound depositional sequences (Missimer, 1997; Weedman et al., 1997; Cunningham et al., 1998; Edwards et al., 1998; Guertin, 1998; Missimer, 1999; Weedman et al., 1999). The purpose of this study is to integrate new lithologic and paleontologic data with established subsurface data to more accurately describe the regional lithostratigraphic and sequence-stratigraphic framework of the Miocene-Pliocene siliciclastics and carbonates of southern Florida. Correlating these data will improve understanding of the regional stratigraphic framework and constrain time boundaries for depositional sequences.

METHODS

A total of 89 coreholes and cuttings from 18 test wells were used to map lithostratigraphic boundaries and to develop facies associations and sequence stratigraphy (Fig. 1 }. The cuttings were described using a binocular microscope. Descriptions of the cores are from Causaras (1985}, Causaras (1987}, Fish (1988}, Fish and Stewart (1991}, McNeill et al. (1996}, Missimer (1997}, Weedman et al. (1997}, Cunningham et al., (1998}, Edwards et al., (1998}, Guertin (1998}, Weedman et al. (1999}, Reese and Cunningham (2000, in press}, and from the data archives of the Florida Geological Survey and U.S. Geological Survey. Co-authors David Bukry and Tokiyuki Sato identified coccolith taxonomy, and John Barron determined diatom taxonomy. Bukry and Barron conducted identifications by standard U.S. Geological Survey methods. Sato identified coccoliths for each sample by counting 200 nannofossil specimens for quantitative analysis. The terms abundant (greater than 32 percent of specimens in total assemblage}, common (32 to 8 percent of specimens in total assemblage}, rare (less than 8 percent of specimens in total assemblage} and present (found but not counted}were used to describe quantitatively coccolith populations defined by Sato. Coccolith taxonomy has been assigned to the biostratigraphic zones of Okada and Bukry (1980} as calibrated to the coccolith datums of ODP Leg 171 B from the Blake Nose east of northern Florida (Shipboard Scientific Party, 1998} with normalized modifications from Bukry (1991 }.

Co-author Laura Guertin identified benthic foraminifera at the genus level using data from Bock et al. (1971}, Poag (1981}, and Jones (1994}. Paleoenvironmental interpretations are based on grouping of individual benthic foraminiferal associations and species into the broad depth categories of inner and outer shelf, defined as mean sea level to an approximate water depth of about 305 feet and from about 305 to 610 feet, respectively (Murray, 1991}. Ages are reported in accordance with the integrated magnetobiochronologic Cenozoic time scale of Berggren et al. (1995}.

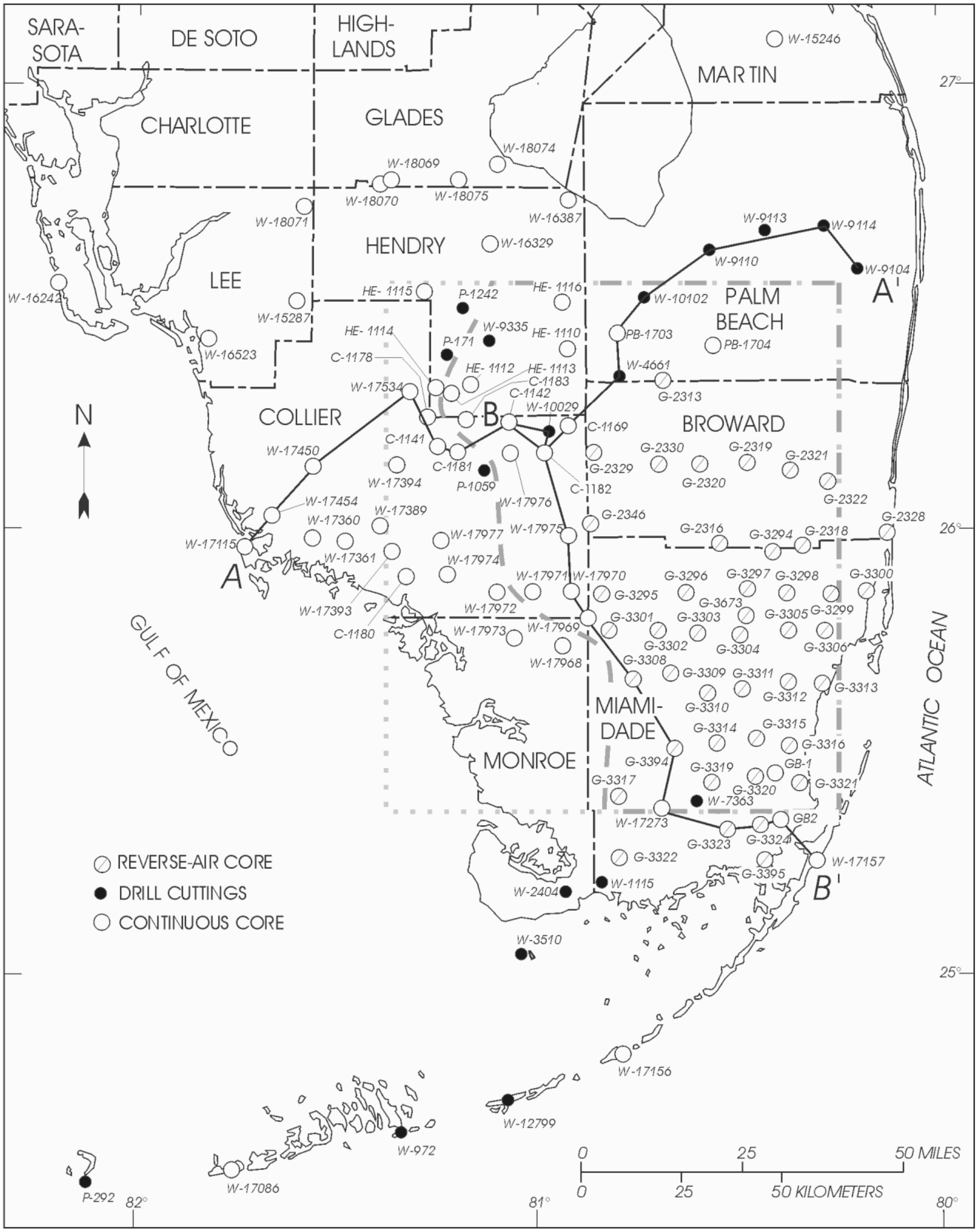

Figure 1. Location map of test wells used in this study. Data from this study, Florida Geological Survey lithologic data base, Causaras (1985, Causaras (1987), Fish (1988), Fish and Stewart (1991), McNeill et al. (1996), Missimer (1997), Weedman et al. (1997), Edwards et al. (1998), Guertin (1998), Weedman et al. (1999), and Reese and Cunningham (2000, in press). The dashed polygon shows the area used to develop facies associations for the upper part of the Peace River Formation (Table 1), and the stippled box indicates the area used for development of the facies associations of the Ochopee Limestone Member of the Tamiami Formation and an unnamed sand (Tables 6 and 7). Locations of cross-sections A-A' (Fig. 5) and B-B' (Fig. 6) are shown.

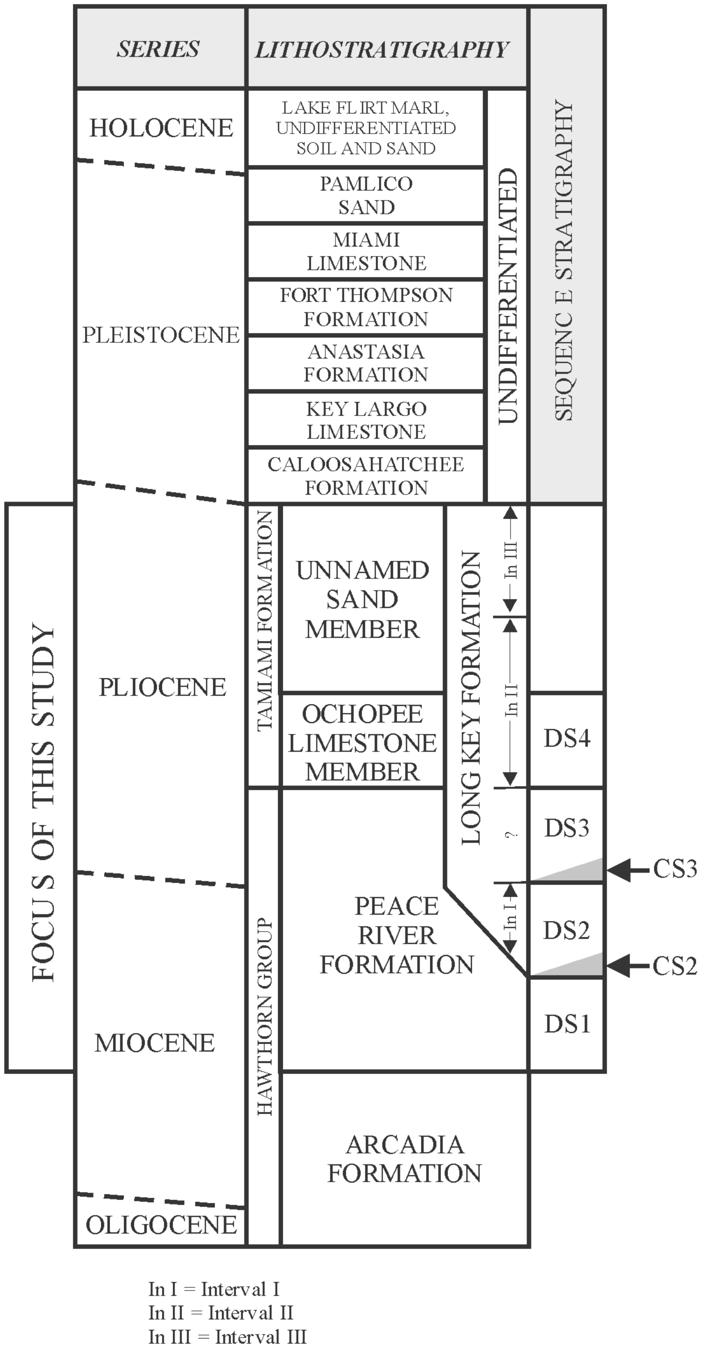

Figure 2. Correlation of chronostratigraphy, lithostratigraphy, and sequence stratigraphy recognized in much of the study area. Modified from Olsson (1964), Hunter (1968), Miller (1990), Missimer (1992), Brewster-Wingard et al. (1997), Missimer (1997), Cunningham et al. (1998), Guertin et al. (1999), Missimer (1999), Weedman et al (1999), and Reese and Cunningham (2000, in press). The Long Key Formation occurs in southernmost peninsular Florida and the Florida Keys (Cunningham et al., 1998). DS1, DS2, DS3, and DS4 are depositional sequences, and CS2 and CS3 are condensed sections. Intervals I, II, and III of Guertin et al. (1999) are integrated into the correlation scheme.

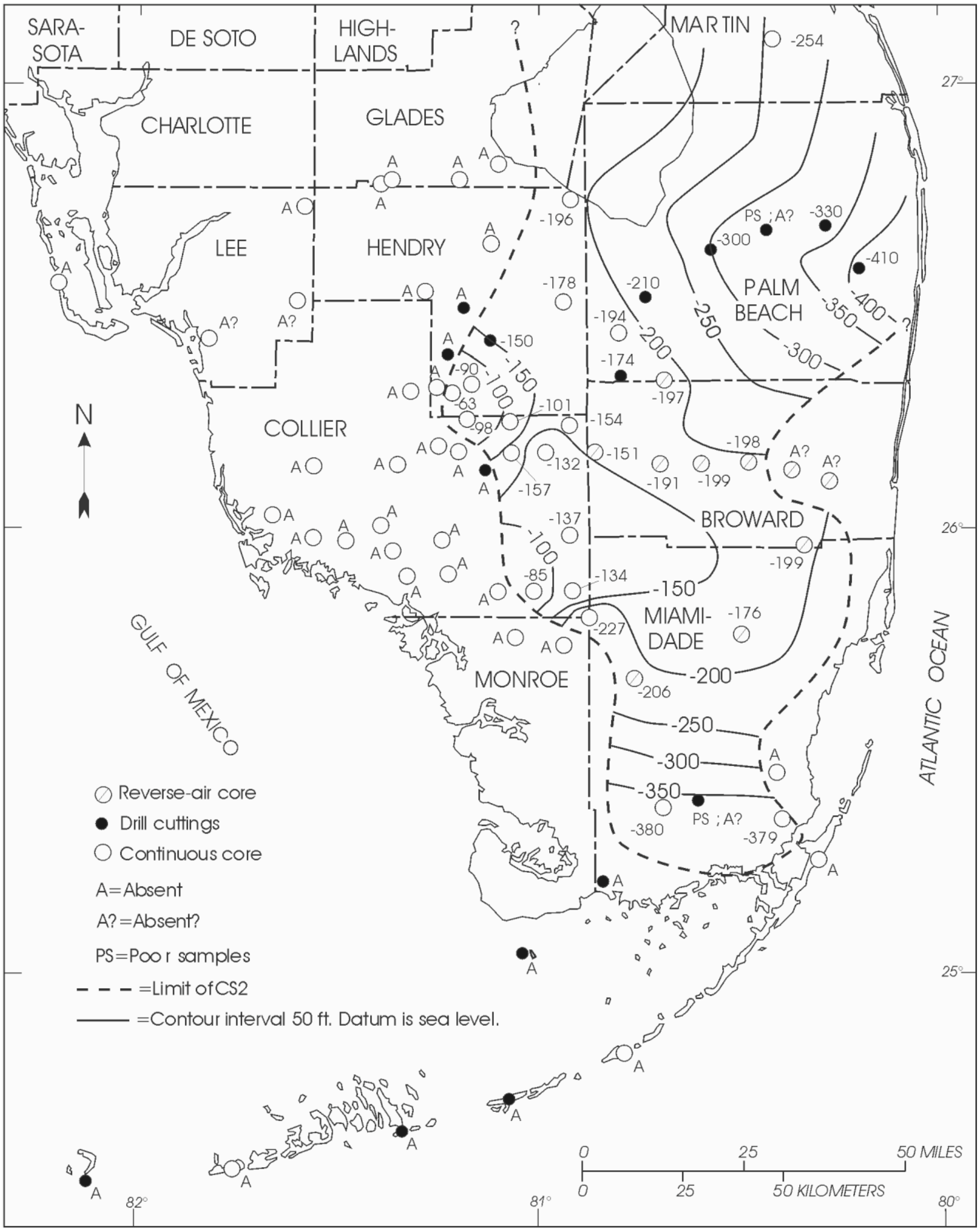

Figure 3. Structure contour map of the top of the mudstone contained in condensed section 2 (CS2) within depositional sequence 2 (DS2) of the Peace River Formation in southern Florida. The dashed line shows the mapped limit of CS2. Structure contours show altitude in feet below sea level of top of the mudstone.

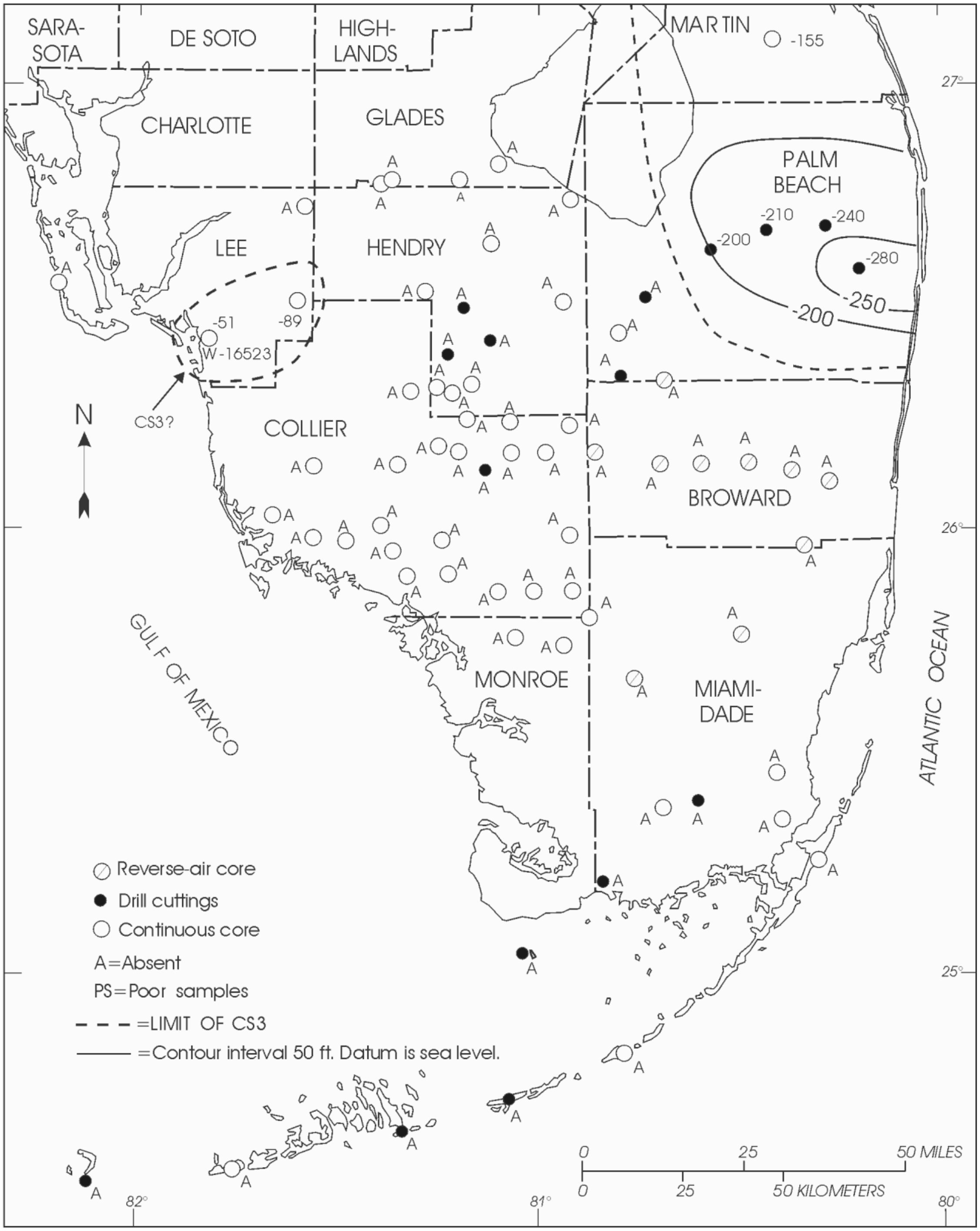

Figure 4. Structure contour map of the top of the mudstone contained in condensed section 3 (CS3) within depositional sequence 3 (DS3) of the Peace River Formation in southern Florida. Both mudstones mapped on the southwestern and southeastern parts of Florida were deposited during the early Pliocene, possibly synchronously, as suggested by dating from Missimer (1997) for the W-16523 corehole in Lee County and the biochronology of the mudstones in Palm Beach and Martin Counties. Structure contours show altitude in feet below sea level of top of the mudstone.

CARBONATE RAMP AND BOUNDING SILICICLASTICS TEMPORAL AND SPATIAL BOUNDARIES

Lithologic units of primary interest in this study, from oldest to youngest, are the Peace River Formation of the Hawthorn Group, Ochopee Limestone Member of the Tamiami Formation, and an unnamed sand member (Fig. 2). Facies associations presented for the Peace River Formation, Ochopee Limestone, and unnamed sand are based on examination of cores and on existing descriptions within the study areas outlined in Figure 1.

Peace River Formation

Lithostratigraphy

Three depositional sequences (DS1, DS2, and DS3) are newly defined on a regional scale within the Peace River Formation (Fig. 2). Although interpreted to be depositional sequences, DS3 actually may be a parasequence. Much of the lithofacies analysis completed by Reese and Cunningham (2000, in press) for southeastern Florida was limited mostly to DS2 and DS3. Depositional sequence 1 (DS1) was characterized primarily by Weedman et al. (1997) and Edwards et al. (1998). Five lithofacies have been identified by Reese and Cunningham (2000, in press) for the upper part of the Peace River Formation in an area shown in Figure 1: (1) diatomaceous mudstone, (2) terrigenous mudstone, (3) clay-rich quartz sand, (4) quartz sand, and (5) pelecypod-rich quartz sand or sandstone (Table 1).

The diatomaceous mudstone and terrigenous mudstone typically occur as a couplet with the diatomaceous mudstone underlying the terrigenous mudstone. Two mudstone couplets were identified as CS2 and CS3 (Fig. 2). Structure contour maps of the two condensed sections show that the lower condensed section (CS2) extends over about 6,000 square miles of southeastern Florida (Fig. 3); the upper condensed section (CS3) is considerably more limited in areal extent (Fig. 4). The lower condensed section (CS2) thins and pinches out in a paleo-landward or western direction (Figs. 5 and 6). The paleo-seaward lap out of CS2 is near the southern margin and probably near the southeastern margin of the Florida peninsula (Figs. 3 and 6). The updip lap out of CS3 is in a paleo-seaward direction from the updip lap out of CS2, suggesting eastward offlapping progradation of Peace River siliciclastics (Fig. 6).

Above the lower mudstone in much of the study area, the Peace River Formation is composed, from bottom to top, of clay-rich quartz sand, quartz sand, and pelecypod-rich quartz sand and sandstone (Table 1). Some of the clay-bearing facies of the Peace River Formation may grade laterally into mainly quartz sand facies in the western part of the study area.

Sequence Stratigraphy

In developing a regional sequence stratigraphy, it is common practice to initially identify the more easily recognized condensed sections of unconformity-bound depositional sequences (Posamentier and James, 1993). In prior studies of the Peace River Formation and equivalent sediments in southern Florida, only bounding unconformities have been proposed (Missimer, 1997; Guertin, 1998; Guertin et al., 1999; Missimer, 1999).

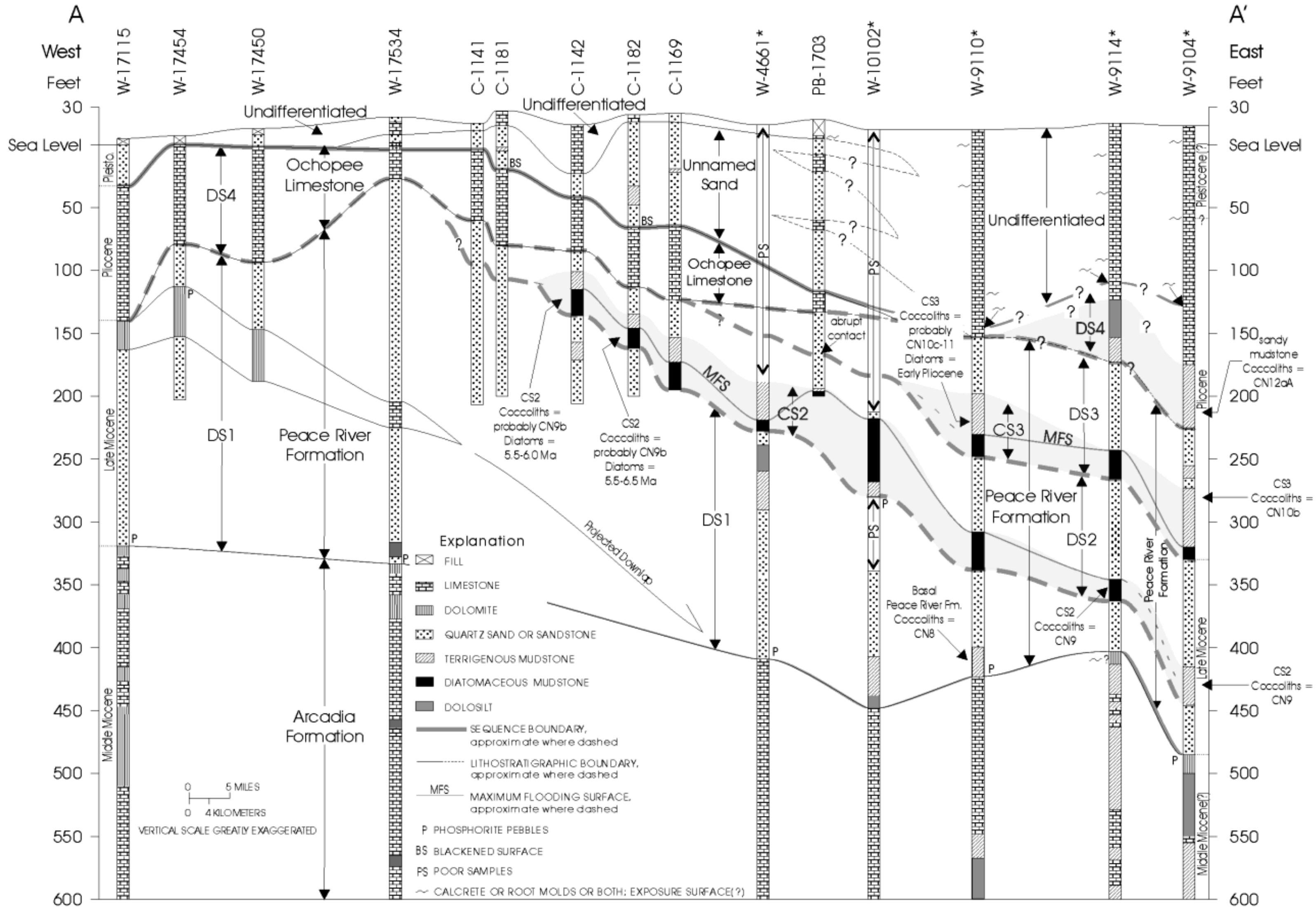

Figure 5. Geologic cross-section A-A' showing lithostratigraphy, sequence stratigraphy, and biostratigraphy of the upper Tertiary of southern Florida. An additional condensed section and possible depositional sequence may occur between DS3 and DS4 in wells W-9114 and W-9104. The location of the lower boundary of DS4 in wells W-9114 and W-9104 above the lower lithostratigraphic boundary of the Ochopee Limestone Member of the Tamiami Formation may be due to poor samples. Portions of some sequence boundaries are equivalent to the parasequence concepts of shoaling-upward cycles bounded by flooding surfaces (Van Wagoner et al., 1988). All lithologic descriptions were taken from continuous cores, except for wells marked by an asterisk which were taken from well cuttings. Location of cross section shown in Figure 1.

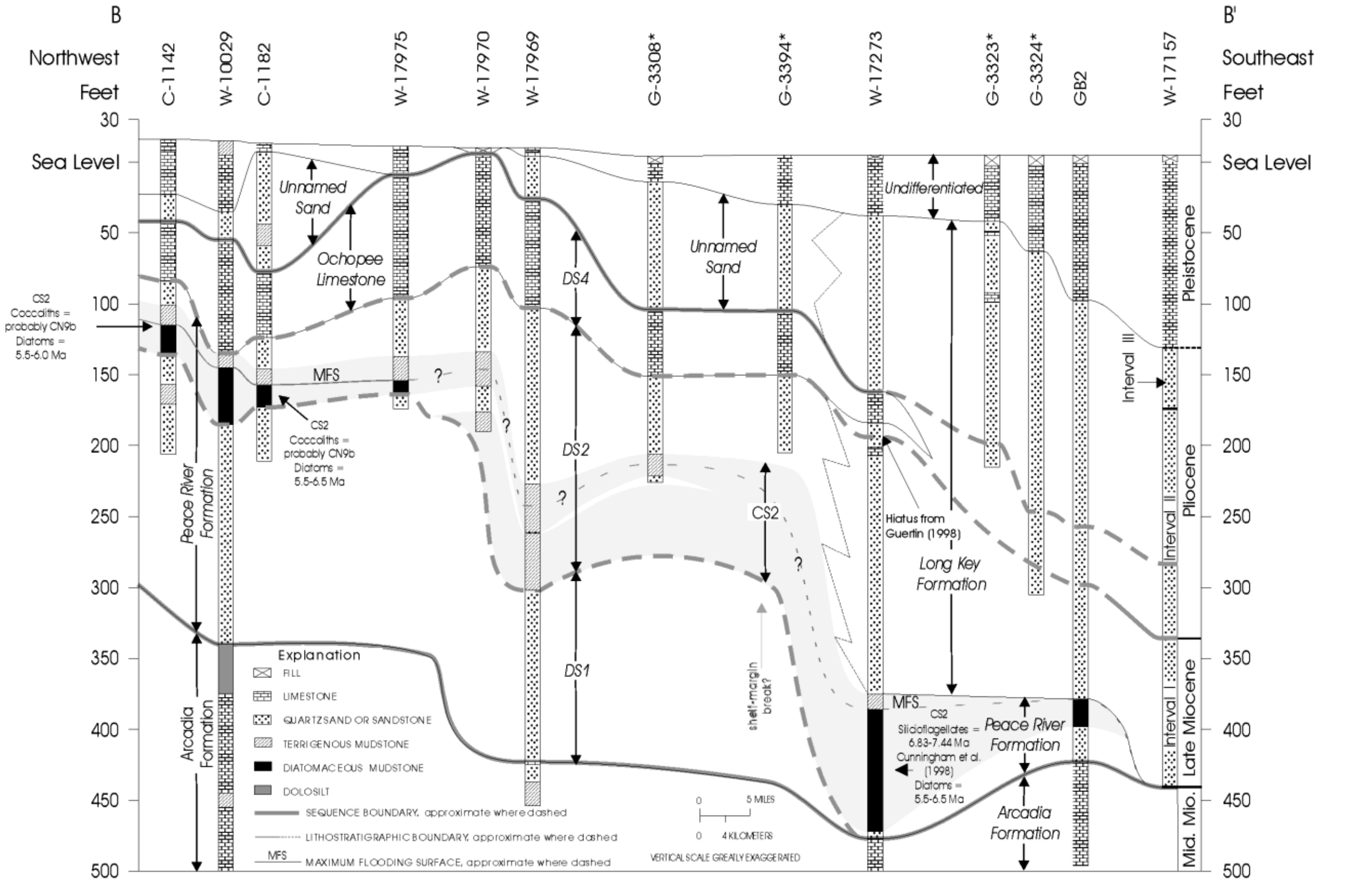

Figure 6. Geologic cross-section B-B' showing lithostratigraphy, sequence stratigraphy, and biostratigraphy of the upper Tertiary of southern Florida. Southern lap out of depositional sequence DS1 and condensed section CS2 within the Peace River Formation and southern lap out of the Ochopee Limestone Member of the Tamiami Formation are shown. Depositional Intervals I, II, and III from Guertin et al. (1999). Portions of some sequence boundaries are equivalent to the parasequence concepts of shoaling upward cycles bounded by flooding surfaces (Van Wagoner et al., 1988). All lithologic descriptions were taken from continuous coreholes, for wells marked by an asterisk which were taken from reverse-air core samples. Location of cross section shown in Figure 1.

Table 1. Lithofacies characteristics of the upper part of the Peace River Formation for the area outlined in Figure 1

[Visual estimation was made for porosity. Hydraulic conductivity was estimated by comparison of corehole from Fish and Stewart (1991, table 6)]

Characteristic	Lithologic description
	Diatomaceous Mudstone Facies
Depositional textures	Diatomaceous mudstone
Color	Mainly yellowish-gray 5Y 7/2 and light-olive-gray 5Y 5/2
Grain size	Mainly terrigenous clay and fine sand-size diatoms; minor silt-size quartz; local very fine sand-size quartz and phosphate grains, and fish scales
Carbonate grains	Local benthic foraminifers
Accessory grains	Common quartz grains and local phosphate grains
Porosity	Minor microporosity
Hydraulic conductivity	Very low (less than 0.1 foot per day)
	Terrigenous Mudstone Facies
Depositional textures	Terrigenous mudstone and claystone
Color	Mainly light-olive-gray 5Y 5/2, yellowish-gray 5Y 7/2, and olive-gray 5Y 4/1, 5Y 3/2
Grain size	Mainly terrigenous clay; minor silt-size quartz; local very fine sand- to granule-size quartz grains and very fine sand- to pebble-size phosphate grains
Carbonate grains	Local benthic foraminifers and pelecypod fragments
Accessory grains	Common quartz grains; local diatoms, phosphate grains, mica, fish scales, shark's teeth
Porosity	Minor microporosity
Hydraulic conductivity	Very low (less than or equal to 0.1 foot per day)
	Clay-Rich Quartz Sand Facies
Depositional textures	Terrigenous clay-rich sand
Color	Mainly yellowish-gray 5Y 7/2 and 5Y 8/1, and light-gray-olive 5Y 6/1
Grain size	Mainly very fine quartz grains; minor silt-size quartz grains and terrigenous mud; local micrite, fine sand-size to small pebble-size quartz grains and very fine sand-size to pebble-size phosphate grains
Carbonate grains	Local thin-shelled pelecypods, oysters, *Turritella* and benthic foraminifers
Accessory grains	Common phosphate grains (trace to 40 percent); minor heavy minerals; trace mica
Porosity	Mainly intergrain; local moldic; ranges from 5 to 20 percent
Hydraulic conductivity	Mainly very low (less than 0.1 foot per day) to low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
	Quartz Sand Facies
Depositional textures	Quartz sand with less than 10 percent skeletal grain
Color	Mainly yellowish-gray 5Y 8/1 and yellowish-gray 5Y 7/2; locally medium-dark-gray N4 to very light gray N8, light-olive-gray 5Y 5/2, grayish-yellow-green 5GY 7/2, pale-olive 10Y 6/2, very pale orange 10YR 8/2, and pale-yellowish-brown 10YR 6/2
Grain size	Mainly very fine to medium quartz sand; ranges from silt to granule size; carbonate grains range from silt to pebble size; terrigenous clay
Carbonate grains	Pelecypods (local *Pecten* and *Chione*), benthic foraminifers, echinoids, and undifferentiated skeletal grains
Accessory grains	Trace to 30 percent phosphate and heavy mineral grains; local minor terrigenous clay; local trace mica; trace to 1 percent plagioclase; trace microcline
Porosity	Intergrain; ranges from 5 to 20 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
	Pelecypod-Rich Quartz Sand or Sandstone Facies
Depositional textures	Quartz sand matrix with pelecypod rudstone framework, or quartz sand supporting skeletal floatstone
Color	Mainly yellowish-gray 5Y 8/1 and 5Y 7/2; locally light-gray N7 to white N9, light-olive-gray 5Y 5/2, light-olive-gray 5Y 6/1, and very pale orange 10YR 8/2
Grain size	Mainly very fine to fine quartz sand; ranges from silt to very coarse quartz sand; carbonate grains range from silt to cobble size; local terrigenous clay and lime mudstone
Carbonate grains	Pelecypods (including *Pecten* and oysters), undifferentiated skeletal grains, gastropods (including *Turritella*), bryozoans, serpulids, and echinoids
Accessory grains	Trace to 40 percent phosphate and heavy mineral grains; local minor terrigenous clay and lime mudstone; local trace mica
Porosity	Intergrain and moldic; ranges from 5 to 25 percent; local abundant pelecypod molds contribute to high porosity
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from very low (less than 0.1 foot per day) to high (100 to 1,000 feet per day)

In the proposed southern Florida sequence stratigraphy for this study, downdip portions of some sequence boundaries are equivalent to the parasequence concept of shoaling-upward cycles bounded by flooding surfaces (Van Wagoner et al., 1988) instead of unconformities. The framework herein provides guidance for further investigation into recognition of unconformities and a more precise definition of sequence boundaries. Additionally, two newly identified condensed sections of the Peace River Formation are placed into the established framework of unconformities. A condensed section is a relatively thin marine stratigraphic unit composed of pelagic to hemipelagic sediments that accumulated at very low sedimentation rates (Loutit et al., 1988). Condensed sections are important for biostratigraphic dating, defining and correlating depositional sequences, and reconstructing depositional environments (Loutit et al., 1988; Posamentier and James, 1993). In much of the study area, the distinct lithology of the condensed sections facilitates their recognition in the context of the proposed developing sequence stratigraphy.

The diatomaceous mudstone that forms the two condensed sections of the Peace River Formation (Figs. 5 and 6) contains a greater concentration of planktic fossils than overlying terrigenous mudstone, suggesting the upper surface of the diatomaceous mudstone defines the surface of maximum flooding within each couplet. The maximum flooding surface represents a time of maximum flooding within a depositional sequence, and marks the change from a transgressive systems tract to a highstand systems tract (Van Wagoner et al., 1988; Posamentier and James, 1993).

Depositional sequence 1 (DS1) is a wedge-shaped deposit of quartz sand, sandstone, and minor carbonate that thins toward the southern and eastern edges of the Florida peninsula. This depositional sequence laps out north of the W-17273 corehole in Miami-Dade County toward the southern edge of the Florida peninsula (Fig. 6). Downlap of internal strata onto the top of the Arcadia Formation is suggested by correlations shown in Figure 5. The southern lap out thinning toward the east and probable downlap to the east suggest progradation of a siliciclastic shelf toward the east and south (Figs. 5 and 6). A shelf-margin break is postulated to occur between the W-17969 and W-17273 cores (Fig. 6).

The bottom of DS1 is delimited by a regional unconformity that separates the Peace River Formation from the Arcadia Formation. This unconformity in southern Florida represents a hiatus of about 1.6 to 11.5 million years based mostly on strontium-isotope chemostratigraphy (Guertin et al., 2000). An unconformity, with local evidence of subaerial exposure (discussed later) defines the top of DS1 in the western part of the study area (Fig. 5). In the east and southeast, the base of a condensed section (CS2) delineates the top of DS1 (Figs. 5 and 6). A sequence stratigraphy produced by Missimer (1999) at the W-17115 corehole in Collier County (Fig. 5) was linked to the sequence stratigraphy developed here, suggesting that DS1 is equivalent to a supersequence defined within the lower Peace River Formation (Fig. 7) by Missimer (1999).

Depositional sequences 2 and 3 (DS2 and DS3) contain coarsening upward siliciclastic deposits defined by mudstone (CS2 and CS3) at the base that grades upward into mostly very fine to fine quartz sand and sandstone (Figs. 5 and 6). Depositional sequence 2 (DS2) has a profile in Figure 6 that thins landward, thickens as fill along the marginal slope of DS1 and thins seaward in cross-section B-B' (Fig. 6). The profile in Figure 5 shows landward thinning of this unit in a sheet like geometry. Most of the base of DS2 is delimited as the base of CS2 (Figs. 5 and 6). Quartz sands in the W-17273 and GB2 coreholes (Fig. 6) form an early transgressive deposit at the base of DS2 that is consistent with palynomorph data presented by Cunningham et al. (1998). These sands and the diatomaceous mudstone of CS2 form the transgressive systems tract of DS2.

Depositional sequence 2 (DS2) is probably equivalent to Interval I of the Long Key Formation (Guertin et al., 1999) in the Florida Keys. This depositional sequence is bounded at the top by an unconformity identified in southernmost Florida by Guertin et al. (1999) at the top of Interval I of the Long Key Formation (Fig. 6). This unconformity is probably regional in extent and may merge to form an amalgamated unconformity with the top of DS1 (Fig. 5). The limits of CS2 in Figure 3 and the cross sections shown in Figures 5 and 6 suggest that southward transport of quartz sand to the Florida Keys during deposition of DS2 was mostly along the southeastern coast of Florida.

Depositional sequence 3 (DS3) is the youngest depositional sequence defined within the Peace River Formation in the study area. The condensed section (CS3) of DS3 seems to be restricted to an area in Martin and Palm Beach Counties and possibly an area mostly contained in Lee County (Fig. 4). Depositional sequence 3 (DS3) contains CS3 as the basal unit in most of the area, and is partly overlain by the Tamiami Formation (Fig. 5). The PB-1703 corehole (Fig. 1) contains an abrupt contact that may be an erosion/truncation surface and may define an unconformity at the base of DS3 (Fig. 5). This potential unconformity may become conformable down dip at the base of CS3 (Fig. 5). An unconformity has not been identified at the top of DS3 in Martin and Palm Beach Counties. An unconformity that bounds the upper Peace River Formation of early Pliocene age in southwestern Florida (Missimer, 1997; 1999) is a depositional sequence possibly equivalent to DS3 based on similar age (Fig. 7).

Micropaleontology

Taxonomic identification of diatoms, silicoflagellates and coccoliths from the Peace River Formation are limited to the condensed sections contained in DS2 and DS3 (Figs. 5 and 6). Micropaleontologic analyses focused on CS2 and CS3 because these mudstone units contain microfossils that are useful for constructing a chronostratigraphy. Examination of samples for benthic foraminifera was conducted on both mudstones and quartz sands of the Peace River Formation. Both the benthic foraminifera and diatom populations were helpful in defining depositional environments.

Diatoms and silicoflagellates

Biostratigraphic analysis of diatoms was conducted on samples from the W-9110, C-1142, C-1182, and W-17273 cores (Table 2). Diatoms from one sample of CS2 in the C-1142 corehole suggest an age of 6.0 to 5.5 Ma (million years ago). Four diatomaceous mudstones samples of CS2 in the W-17273 corehole and one sample from the C-1182 corehole contain very similar diatom assemblages. A latest Miocene age older than 5.5 Ma is suggested for CS2 in both of these cores based on the absence of *Thalassiosira oestrupii,* which first occurs at 5.5 Ma (Fig. 7). Other diatoms present in the assemblage *(Paralia sulcata, Stephanopyxis sp., Delphineis sp., Actinoptychus sp., Actinocyclus octonarius, Thalassionema nitzschioides, Thalassiosira eccentrica, Thalassiosira leptopus, Koizumia adaroi,* and early forms of *Koizumia tatsunokuchiensis)* are consistent with an age younger than 6.5 Ma (Yanagisawa and Akiba, 1998; J.A. Barron, U.S. Geological Survey, written commun., 2000).

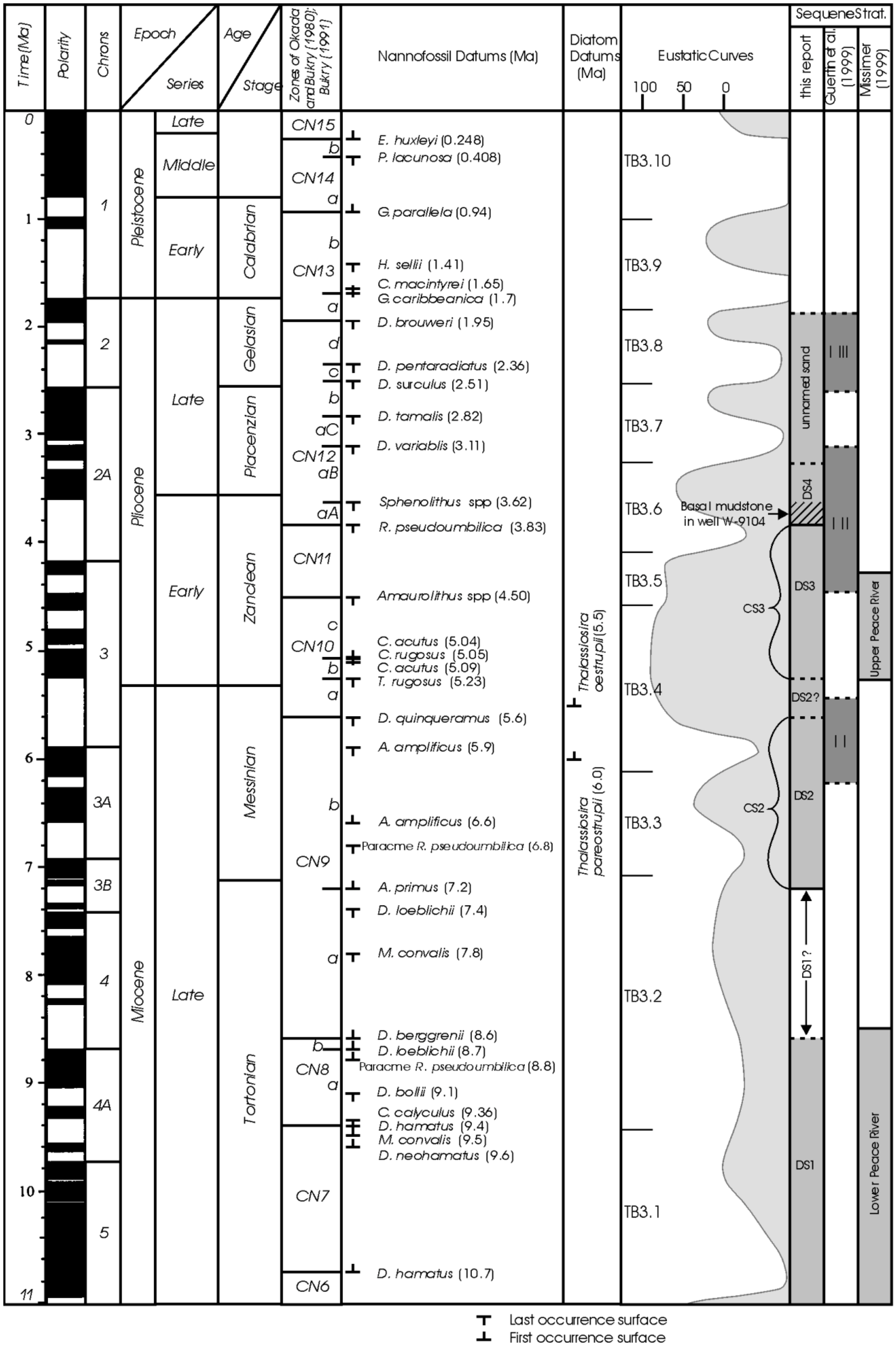

Figure 7. Correlation of the chronostratigraphy of a portion of the late Tertiary geomagnetic polarity time scale (Berggren et al., 1995) and coccolith zonation. From ODP Leg 171B at the Blake Nose east of northern Florida (Shipboard Scientific Party, 1998) with normalized additions of Subzones CN12aA, aB, and aC from Bukry (1991), the eustatic curves of Haq et al. (1988), diatom datums from offshore California, and southern Florida sequence stratigraphy.

Table 2. Occurrence of stratigraphically important diatom taxa and the silicoflagellate *D. frugalis* in wells W-9110, C-1142, C-1182 and W-17273

[CS2, condensed section 2 of the Peace River Formation; CS3, condensed section 3 of the Peace River Formation; <, less than the value. Genus: DF, *Distephanus frugalis*; HO, *Hemidiscus ovalis*; KA, *Koizumia adaroi*; KT, *K. tatsunokuchienis*; RF, *Rhaphoneis fatula*; TE, *Thalassiosira eccentrica*; TO, *T. oestrupii*; TP, *T. praeoestrupii*]

Well No.	Sample depth (feet below sea level)	Sample type	Strati-graphic unit	Subepoch	Esti-mated age (million years ago)	Genus present							
						DF	HO	KA	KT	RF	TE	TO	TP
W-9110	208-218	Cuttings	CS-3	Early Pliocene	<5.5				X	X	X	X	
	238-248	Cuttings	CS-3	Early Pliocene	<5.5		X		X	X	X	X	
C-1142	123.2	Core	CS-2	Late Miocene	6.0 - 5.5			X			X		X
C-1182	147.5	Core	CS-2	Late Miocene	6.0 - 5.5			X	X		X		
W-17273	410.0	Core	CS-2	Late Miocene	6.5 - 5.5			X	X		X		
	430.0	Core	CS-2	Late Miocene	6.5 - 5.5	X		X	X		X		
	445.0	Core	CS-2	Late Miocene	6.5 - 5.5			X	X		X		
	455.0	Core	CS-2	Late Miocene	6.5 - 5.5			X	X		X		

The diatom analyses herein suggest that the age of CS2 can be constrained to 6.5 to 5.5 Ma. The presence of the silicoflagellate *Distephanus frugalis* in the W-17273 corehole supports an age younger than 6.5 Ma (Barron, 1976). Alternatively, prior work by Cunningham et al. (1998) reported the age of the diatomaceous mudstones (CS2) of the Peace River Formation in the W-17273 corehole to range from 7.44 to 6.83 Ma (Fig. 6). This time frame brackets the Tortonian-Messinian boundary based on the presence of two cosmopolitan silicoflagellate species *Distephanus pseudofibula* and *Bachmannocena triodon* (Cunningham et al., 1998). The 7.44 to 6.83 Ma range in age is consistent with the broader age range for biostratigraphic assignment of coccoliths from CS2 (Zone CN9, perhaps only Zone CN9b) as shown in Figure 7.

The assemblages from the C-1142, C-1182, and W-17273 cores are composed predominantly of shelf-dwelling taxa. The diatomaceous mudstones in the C-1142 and C-1182 cores record a transgressive event, upwelling of nutrients, or possibly both across a siliciclastic shelf as indicated by the dominance of the shelf-dwelling taxa. The diatomaceous mudstones of the W-17273 corehole (Fig. 6) also contain an abundance of shelf-dwelling taxa, but the stratigraphic position of the taxa (Fig. 6) suggests deposition in a shelf-slope or toe-of-slope environment. Environmental conditions such as currents, wave sweeping, or both could explain the transport of shelf-dwelling taxa into this off-shelf environment.

Two samples of well cuttings from upper and lower parts of CS3 were collected for analysis from well W-9110 (Fig. 5 and Table 2). The upper sample (Table 2, 208-218 feet below sea level) is from the terrigenous mudstone facies (Table 1), and the lower sample (Table 2, 238-248 feet below sea level) is from the diatomaceous mudstone facies (Table 1). A maximum flooding surface separates the two samples (Fig. 5).

The sample from the upper part of CS3 in well W-9110 contains Paralia sulcata, Actinocyclus octonarius, Actinoptychus senarius, Stephanopyxis sp., Koizumia tatsunokuchienis, Thalassionema nitzschioides, Thalassiosira eccentrica, Thalassiosira leptopus, Thalassiosira oestrupii, and Rhaphoneis fatula. An occurrence of T. oestrupii suggests an age younger than 5.5 Ma (Fig. 7). A rare presence of R. fatula suggests an early Pliocene age based on comparison with occurrences in California (Dumont and Barron, 1995). An abundant presence of *P. sulcata* possibly indicates that this is an outer shelf assemblage (Sancetta, 1981).

The lower sample from CS3 in well W-9110 contains an assemblage similar to the sample from the upper portion but yields few *Paralia sulcata.* In addition to the taxa identified in the upper sample, the lower sample includes the occurrence of *Hemidiscus ovalis.* The presence of *Thalassiosira oestrupii* (Fig. 7) and *H. ovalis* indicates an early Pliocene age (Dumont and Barron, 1995). Planktic diatoms are more common in the sample from the lower part (diatomaceous mudstone facies) of CS3 relative to the upper part of the sequence (terrigenous mudstone facies). Relatively more planktic diatoms in the sample from the lower portion of CS3 is consistent with greater interpreted water depth during deposition of the diatomaceous mudstone relative to the terrigenous mudstone above the maximum flooding surface. This surface is defined by the boundary between the diatomaceous mudstone and terrigenous mudstone (Fig. 5).

Coccoliths

Samples were collected for analysis of coccoliths from wells C-1142, C-1182,W-9104, W-9110, W-9114, and W-17273. These samples were taken from a terrigenous mudstone near the base of the Peace River Formation and the two condensed sections (CS2 and CS3) of the Peace River Formation (Figs. 5 and 6). A single sample from the terrigenous mudstone near the base of the Peace River in well W-9110 (Fig. 5) contains abundant coccoliths that include *Discoaster bellus, Discoaster brouweri, Discoaster prepentaradiatus,* and a questionable *Discoaster bollii.* The assemblage of coccoliths probably belongs to Zone CN8 (Fig. 7), suggesting a Tortonian age (Perch-Nielsen, 1985).

Coccolith and diatom occurrences suggest assignment of CS2 to Subzone CN9b, but could be as old as Zone CN9 and as young as Subzone CN10a (Fig. 7). Coccoliths contained in eight samples from CS2 in the C-1182 corehole suggest assignment of CS2 to Subzone CN9b (7.2-5.6 Ma) based on the presence of *Discoaster berggrenii, Discoaster quinqueramus, Discoaster surculus,* and *Amaurolithus primus* (Fig. 7). Reworking of coccoliths in samples from the C-1182 corehole was investigated, but is unlikely since no uniquely older or younger taxa were identified. Two samples from CS2 in the C-1142 corehole contain D. surculus and thus are no older than Zone CN9. The upper biostratigraphic range of the C-1142 corehole sample is indefinite and assigned to Zone CN9 or Subzone CN10a, but associated diatoms are late Miocene; therefore, samples of CS2 from both the C-1182 and C-1142 cores suggest a late Miocene age no older than Zone CN9 or probably Subzone CN9b (Figs. 5 and 6). The occurrence of the coccoliths *D. quinqueramus and D. berggrenii* in one sample of CS2 collected from well W-9104 and another of CS2 from well W-9114 suggests that CS2 in these wells belongs to Zone CN9 (Fig. 5 and Table 3).

Combined diatom and coccolith data suggest assignment of CS3 to Subzone CN10b through Zone CN11 or early Pliocene (Fig. 7). Coccoliths from CS3 in well W-9104 are characterized by the presence of *Ceratolithus acutus, Ceratolithus armatus,* and *Amaurolithus primus* (Plate 1 and Table 3). These taxa and especially the presence of *C. acutus* indicate assignment of CS3 to Subzone CN10b (5.23-5.05 Ma) and an early Pliocene age (Fig. 7; Table 3). Two samples from CS3 in well W-9110 contain a trace to sparse presence of coccoliths including *Discoaster surculus, Ceratolithus rugosus, and Reticulofenestra pseudoumbilica.* These coccoliths are consistent with assigning CS3 in well W-9110 to Subzones CN10c through Zone CN11 (5.05-3.83) and an early Pliocene age (Fig. 7).

Plate 1. Photographs of coccoliths from well W-9104. Photographs 1 to 16 are from a sample interval of 318 to 328 feet below sea level. Photographs 17 to 20 are from a sample interval of 428 to 438 feet below sea level.

1a,b. *Coccolithus pelagicus* (Wallich) Schiller: (1a) cross-polarized light, and (1b) plane light.

2a,b. *Calcidiscus leptoporus* (Murray and Blackman) Loeblich and Tappan: (2a) cross-polarized light, and (2b) plane light.

3a,b. *Calcidiscus macintyrei* (Bukry and Bramlette) Loeblich and Tappan: (3a) cross-polarized light, and (3b) plane light.

4a,b. *Reticulofenestra pseudoumbilica* (Gartner) Gartner: (4a) cross-polarized light, and (4b) plane light.

5a,b. *Reticulofenestra pseudoumbilica* (Gartner) Gartner: (5a) cross-polarized light, and (5b) plane light.

6a,b. *Sphenolithus abies* Deflandre: (6a) cross-polarized light, and (6b) plane light.

7a,b. *Ceratolithus armatus* Muller: (7a) cross-polarized light, and (7b) plane light.

8a,b. *Ceratolithus armatus* Muller: (8a) cross-polarized light, and (8b) plane light.

9a,b. *Ceratolithus armatus* Muller: (9a) cross-polarized light, and (9b) plane light.

10a,b.*Amaurolithus primus* (Bukry and Percival) Gartner and Bukry: (10a) cross-polarized light, and (10b) plane light.

11. *Discoaster brouweri* Tan. Plane light.

12. *Discoaster brouweri* Tan. Plane light.

13. *Discoaster pentaradiatus* Tan. Plane light.

14. *Discoaster pentaradiatus* Tan. Plane light.

15. *Discoaster surculus* Martini and Bramlette. Plane light.

16. *Discoaster surculus* Martini and Bramlette. Plane light.

17. *Discoaster quinqueramus* Gartner. Plane light.

18. *Discoaster quinqueramus* Gartner. Plane light.

19. *Discoaster berggrenii* Bukry. Plane light.

20. Discoaster berggrenii Bukry. Plane light.

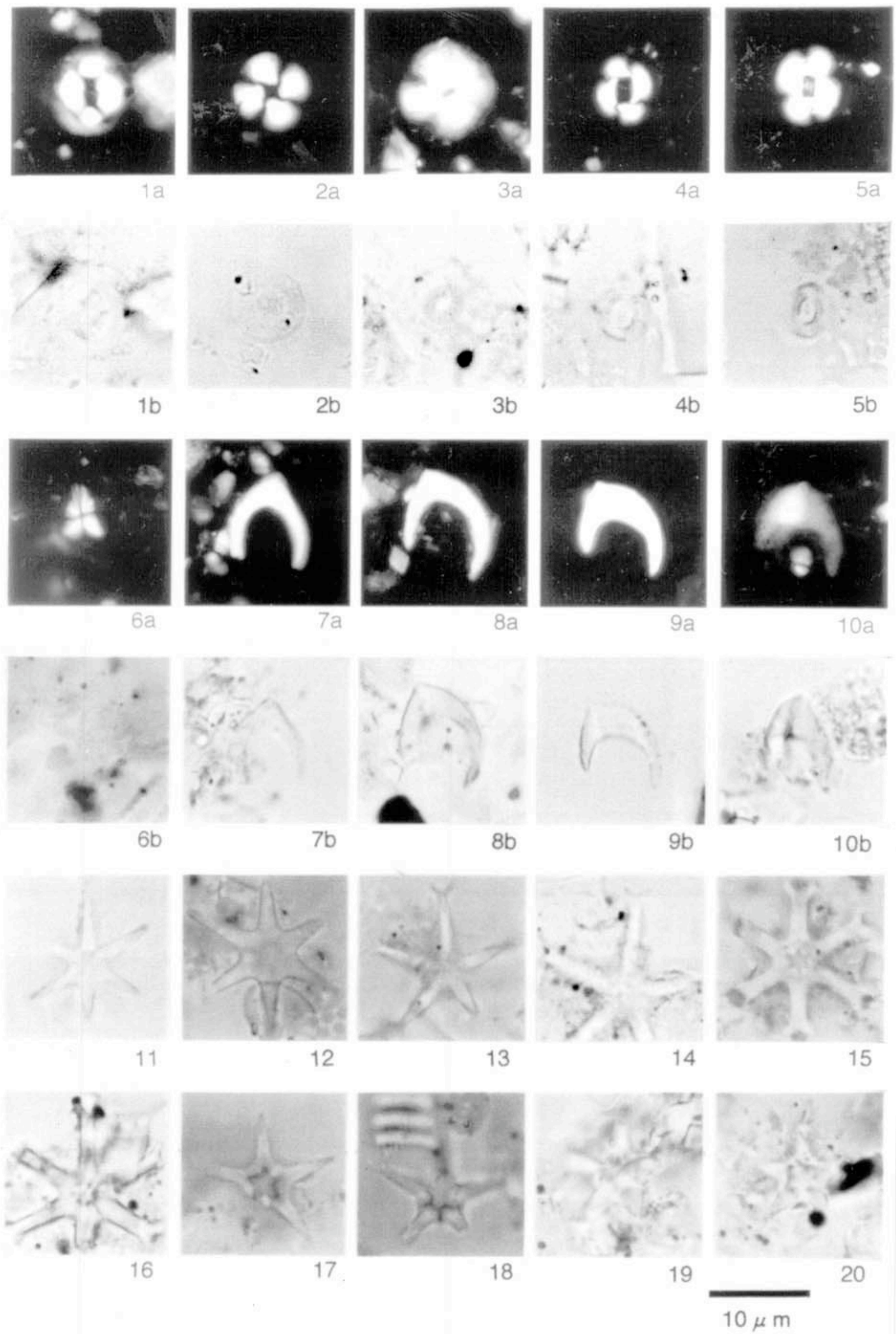
1a
2a
3a
4a
5a
1b
2b
3b
4b
5b
6a
7a
8a
9a
10a
6b
7b
8b
9b
10b
11
12
13
14
15
16
17
18
19
20
10 μm

Table 3. Occurrence of coccolith taxa in cuttings from wells W-9104 and W-9114

[Stratigraphic position: CS2, condensed section 2 of the Peace River Formation; CS3, condensed section 3 of the Peace River Formation; DS4, depositional sequence 4; BPR, base of Peace River Formation. Genus: C, *Ceratolithus rugosus*; CP, *Coccolithus pelagicus*, D, *Dictyococcites* sp. (small); DB, *Discoaster bellus*; DBE, *Discoaster berggrenii*; DBR, *Discoaster brouweri*; DP, *Discoaster pentaradiatus*; DQ, *Discoaster quinqueramus*; DS, *Discoaster surculus*; DSP, *Discoaster* sp; DV, *Discoaster variabilis*; HN, *Helicosphaera neogranulata*; RP, *Reticulofenestra pseudoumbilica*; RS, *Reticulofenestra* sp. (small); SA, *Sphenolithus abies*. Other abbreviations: A, abundant (greater than 32 percent of specimens in total assemblage); C, common (32 to 8 percent of specimens in total assemblage); R, rare (less than 8 percent of specimens in total assemblage; P, present (found but not counted); S, sparse or poorly preserved; ?, not determined]

Well No.	Sample depth (feet below sea level)	Strati-graphic position	Nanno-fossil abun-dance	Nanno fossil zone	Genus present														
					C	CP	D	DB	DBE	DBR	DP	DQ	DS	DSP	DV	HN	RP	RS	SA
C-1142	132	CS2	Barren	--															
W-9104*	205 – 215	DS4	?	CN12aA						P	P		P	P	P				
	315 – 325	CS3	Abundant	CN10b		C	A			P	P		P	C		P	P	A	P
	325 – 335	CS2	Abundant	CN9		P			P			P	P	P			C	A	R
W-9110	208-218	CS3	?	CN9-12									S						
	238-248	CS3	?	CN10c-11	S												S		
	308-318	CS2	Barren	--															
	328-338	CS2	Barren	--															
	408-418	BPR	?	CN8				S		S	S								
W-9114	253 – 263	CS3	Barren	--															
	353 – 363	CS2	Rare	CN9					P			P	P	P			P	P	P
W-17273	415	CS2	Barren	--															
	425	CS2	Barren	--															
	450	CS2	Barren	--															
	460	CS2	Barren	--															

*The following genera also are present (found but not counted) in well W-9104 at a depth interval of 315 to 325 feet: *Acanthoica* sp., *Amaurolithus primus*, *Calcidiscus leptoporus*, *Calcidiscus macintyrei*, *Ceratolithus acutus*, and *Ceratolithus armatus*.

Benthic foraminifera

Nine samples from CS2 were examined for benthic foraminifera. The benthic foraminifera of CS2 belong to a marine shelf assemblage. Two samples from CS3 were examined. The assemblage present in CS3 is consistent with deposition on a marine shelf (Tables 4 and 5).

Ochopee Limestone Member of the Tamiami Formation

Lithostratigraphy and Depositional Environments

The Ochopee Limestone Member of the Tamiami Formation (Hunter, 1968; Meeder, 1987; Missimer, 1992; Edwards et al., 1998; Weedman et al., 1999) includes a regionally extensive limestone facies that can be mapped throughout much of the study area (Fig. 8). The Ochopee Limestone has a sheet-like geometry that drapes over an unconformity at the top of the Peace River Formation (Figs. 5 and 6). The Ochopee Limestone represents a shift in sedimentation on the Florida Platform from the retrogradation of DS3 within the Peace River Formation to

Table 4. Benthic foraminiferal genera and their distribution with depth in wells W-9104, W-9114, C-1169, PB-1703 and C-1142

[Seven samples are not included in this table due to barren results. Stratigraphic position: DS2, depositional sequence 2 of the Peace River Formation; DS3, depositional sequence 3 of the Peace River Formation, US, unnamed sand. Genus: A, *Archaias*; BO, *Bolivina*; BU, *Bulimnella*; C, *Cancris*; CA, *Cassidulina*; CI, *Cibicides*; CR, *Cribroel- phidium*; E, *Eponides*; F, *Fursenkoina*; H, *Henzawaia*; N, *Nonion*; NO, *Nonionella*; R, *Rosalina*]

Well No.	Sample depth (feet below sea level)	Sample type	Strati-graphic position	Genus present												
				A	BO	BU	C	CA	CI	CR	E	F	H	N	NO	R
W-9104	315 – 325	Cuttings	DS3									X			X	
W-9114	253 – 263	Cuttings	DS3	X												
C-1169	163.0	Core	DS2			X							X	X		
	179.0	Core	DS2			X	X				X	X		X	X	X
P-1703	55.9	Core	US			X			X		X		X	X		X
	181.0	Core	DS2											X		
C-1142	131.5	Core	DS2			X					X		X	X		
	134.0	Core	DS2			X					X	X	X	X		
	139.0	Core	DS2			X							X	X		
	144.0	Core	DS2			X		X		X		X	X	X	X	
	149.0	Core	DS2		X	X	X			X	X	X	X	X	X	
	154.0	Core	DS2		X	X	X			X	X	X	X	X	X	

Table 5. Ecological data for benthic foraminiferal genera identified in the W-17614, PB-1703 and C-1142 coreholes

[Depth and environment information according to Murray (1991). Environment information for *Cribroelphidium* according to Bock et al. (1971). >, greater than the value]

Genus	Approximate depth (feet)	Environment
Archaias	0 – 66	Inner shelf
Bulimnella		Lagoon, shelf, upper bathyal
Cancris	164 - 492	Shelf
Cassidulina		Shelf
Cibicides	0 - >6,562	Lagoon, shelf-bathyal
Cribroelphidium		Florida; away from reef
Eponides		Shelf-abyssal
Fursenkoina	0 - 3,937	Lagoon, shelf, upper bathyal
Hanzawaia		Inner shelf
Nonion	0 – 591	Shelf
Nonionella	33 - 3,281	Shelf
Rosalina	0 – 328	Lagoon, inner shelf

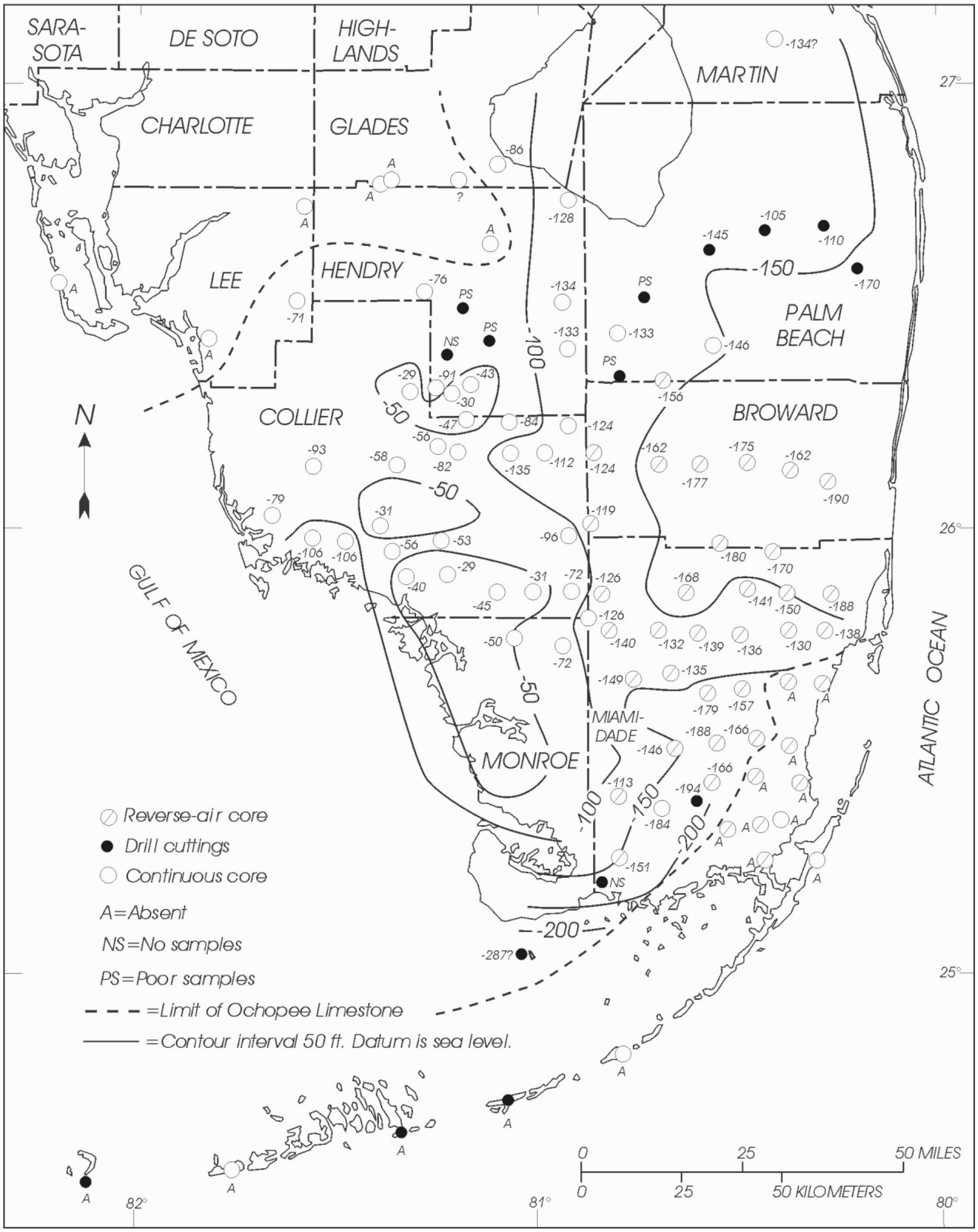

Figure 8. Structure contour map of the base of the Ochopee Limestone Member of the Tamiami Formation. Structure contours show altitude in feet below sea level of base of the Ochopee Limestone.

Table 6. Lithofacies characteristics of the Ochopee Limestone Member of the Tamiami Formation for the area outlined in Figure 1

[Visual estimation was made for porosity. Hydraulic conductivity was estimated by comparison of corehole from Fish and Stewart (1991, table 6)]

Characteristic	Lithologic description
Pelecypod Lime Rudstone or Floatstone Facies	
Depositional textures	Pelecypod lime rudstone or floatstone with quartz sand-rich lime packstone or grainstone matrix
Color	Mainly medium-light-gray N6 to very light gray N8 and yellowish-gray 5Y 8/1; locally yellowish-gray 5Y 7/2, black to medium-gray N5, white N9, and very pale orange 10YR 8/2
Grain size	Carbonate grains range from silt to cobble size; quartz sand mainly very fine to fine, ranges from silt to very coarse
Carbonate grains	Pelecypods (local oysters, *Pecten*, *Chione*, and *Ostrea*), undifferentiated skeletal fragments, bryozoans, gastropods (local *Turritella* and *Vermicularia*), benthic foraminifers, echinoids, serpulids, barnacles, planktic foraminifers, ostracods, encrusting foraminifers, corals (hermatypic)
Accessory grains	Common quartz sand and phosphate grains
Porosity	Mainly intergrain and moldic; local intrafossil and boring; ranges from 5 to 25 percent
Hydraulic conductivity	Mainly moderate (10 to 100 feet per day); ranges from low (0.1 to 10 feet per day) to high (100 to 1,000 feet per day)
Pelecypod-Rich Quartz Sand or Sandstone Facies	
Depositional textures	Pelecypod-rich quartz sand and quartz-rich sandstone
Color	Mainly yellowish-gray 5Y 8/1 and light-gray N7 to very light gray N6; locally medium-dark-gray N4 to medium-light-gray N6, very pale orange 10YR 8/2, light olive-gray 5Y 6/1, yellowish-gray 5Y 7/2, and pale-yellowish-brown 10YR 6/2
Grain size	Mainly very fine to fine quartz sand; ranges from silt to coarse quartz sand; carbonate grains range from silt to cobble size
Carbonate grains	Pelecypods (local oysters), undifferentiated skeletal fragments, gastropods, echinoids, barnacles, serpulids, intraclasts, bryozoans, and encrusting foraminifers
Accessory grains	Absent to 5 percent phosphate and heavy mineral grains; local minor terrigenous clay or lime mudstone matrix
Porosity	Mainly intergrain with local moldic and intragrain; ranges from 10 to 20 per cent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day)

aggradation of the Ochopee Limestone. The Ochopee Limestone laps out near the southern margin of the Florida peninsula. The lapout is probably coincident with the edge of the siliciclastic shelf containing DS2 of the Peace River Formation (Fig. 6).

Two lithofacies characterize the Ochopee Limestone in an area shown in Figure 1: (1) pelecypod lime rudstone or floatstone, and (2) pelecypod-rich quartz sand or sandstone (Table 6). The rudstone or floatstone facies is the most common lithofacies, whereas the sand or sandstone facies occurs only locally as thin to thick beds. The quartz sand is typically very fine to fine grained, but locally may range from silt to very coarse sand. Skeletal carbonate grains of the pelecypod lime rudstone or floatstone include fossils listed in Table 6.

The Ochopee Limestone was deposited in a carbonate ramp depositional system (Burchette and Wright, 1992) during a reduction in siliciclastic supply to much of southern Florida. Criteria to support the environmental interpretation include: (1) a low basinward depositional gradient of less than 1 degree without a break in slope, as suggested by the upper and lower lithostratigraphic boundaries (Fig. 6); (2) widespread continuity of facies patterns; and (3) an almost complete absence of internal exposure surfaces. In the study area, most of the Ochopee Limestone was deposited in a mid-ramp depositional environment (Burchette and Wright, 1992). Evidence for this depositional environment is indicated by the common occurrence of coarse-grained lime rudstone that has a well washed, grain-dominated matrix (Lucia, 1995) and limemud-rich floatstone (Table 6). The mixture of these grain-dominated and mud-dominated carbonates and the lack of shallow-water faunal indicators suggest deposition below fair-weather wave base (FWWB) but above storm wave base (SWB). The zone between FWWB and SWB defines the mid-ramp depositional environment of Burchette and Wright (1992). Planktic foraminifera-rich sandstone--similar to lithofacies of the Stock Island Formation of Cunningham et al. (1998)--between depths of 275 and 336 feet below sea level in the W-17157 corehole may represent a distal portion of the Ochopee ramp that accumulated in relatively deep sea water (Fig. 6). Although the Ochopee Limestone contains quartz sand, the overwhelming abundance of carbonate grains represents a period of reduced quartz sand, silt, and mud to the southern Florida Platform.

The benthic carbonate grains of the Ochopee Limestone represent a heterozoan particle association, which James (1997) defined as a group of carbonate particles produced by light-independent, benthic organisms that may or may not contain red calcareous algae. Red algae were not observed in the Ochopee Limestone within the study area. The predominately heterozoan assemblage of carbonate particles and an absence of shallow-marine particles, such as ooids and green algae, is consistent with deposition in a mid-ramp depositional environment with temperate bottom-water conditions. An almost complete absence of exposure surfaces within the Ochopee Limestone is also consistent with mid-ramp deposition at water depths sufficient to minimize changes in water-bottom conditions during low-amplitude changes in relative sea level.

Sequence Stratigraphy

Depositional sequence 4 (DS4) is bounded at the base and top by regional subaerial unconformities and is composed of the Ochopee Limestone (Figs. 5 and 6). The regional-scale sequence boundary at the base of the Ochopee Limestone is evidenced by several established unconformities reported between the top of the Peace River Formation and the base of the Tamiami Formation in southwestern Florida (Edwards et al., 1998; Missimer, 1999). An unconformity and sequence boundary reported by Missimer (1999) separating the Peace River Formation and the Tamiami Formation in southwestern Florida is probably equivalent to the unconformity separating Intervals I and II of the Long Key Formation (Fig. 6) in the Florida Keys (Guertin et al., 1999). This unconformity may also be present as a hiatus identified by Guertin (1998) in the W-17273 corehole of Miami-Dade County (Fig. 6). A subaerial exposure surface occurs in the W-17394 corehole (Fig. 1) between the top of an unnamed quartz sand that is equivalent to the top of the Peace River Formation (this study) and the Ochopee Limestone in Collier County (Edwards et al., 1998). The unconformity recognized in southwestern Florida (Missimer, 1999), in the W-17157 corehole (Guertin et al., 1999), in the W-17273 corehole (Guertin, 1998), and in the W-17394 corehole (Edwards et al., 1998) all occur near the Miocene-

Pliocene boundary, suggesting that these unconformities may form a correlative sequence boundary of regional scale (Fig. 6).

The top of the Ochopee Limestone is interpreted to represent a depositional sequence boundary. Typically, the contact between the top of the Ochopee Limestone and the unnamed sand is abrupt. Several coreholes (Fig. 1; C-1181 , C-1182, and G-3673) contain an abrupt contact with core-scale microtopography, small dissolution cavities filled with quartz sand of the unnamed sand, and local blackened crust. Blackened surfaces are reported to characterize the tops of late Neogene unconformities bounding depositional sequences in southwestern Florida (Evans and Hine, 1991). Analyses by x-ray diffraction indicate the blackened surfaces at the top of the Ochopee Limestone do not contain a measurable amount of phosphorite. The absence of phosphorite possibly suggests that the surface is not a submarine hardground and condensed section (Loutit et al., 1988). The blackening could be due to fire above the surface during subaerial exposure (Shinn and Lidz, 1988) or to darkened organic matter in soilstone crusts as noted by Ward et al. (1970).

At the C-1178 corehole in Collier County (Fig. 1), the upper bounding surface of the Ochopee Limestone contains strong evidence for subaerial exposure (Reese and Cunningham, 2000, in press). Reese and Cunningham (2000, in press) describe an exposure zone (30 feet thick) bounding the top of the Ochopee Limestone that contains root molds lined with calcrete. This unconformity is postulated to be equivalent to a lithofacies boundary in the Long Key Formation at the W-17157 corehole in the Florida Keys. Along this boundary, there is an upward shift from foraminifera-rich quartz sandstones--similar to lithofacies of the Stock Island Formation of Cunningham et al. (1998)--to overlying quartz sandstone at a depth of 280 feet below sea level (Guertin, 1998) as shown in Figure 6.

Micropaleontology

One sample of well cuttings was collected for analysis of coccoliths from well W-9104. This sample was taken from a sandy mudstone at the base of the Tamiami Formation and possible basal Ochopee Limestone at a depth interval of 205 to 215 feet below sea level (Fig. 5). Coccoliths from the interval are assigned to the early Pliocene Sub zone CN12aA (Fig. 7) identified by Bukry (1991). Coccoliths present in this interval include *Discoaster brouweri*, *D. surculus*, *D. variabilis*, and *Sphenolithus abies*. *Reticulofenestra pseudoumbilica* is absent. This assemblage along with the absence of *R. pseudoumbilica* is characteristic of Subzone CN12aA (Bukry, 1991).

Unnamed Sand

Lithostratigraphy

An unnamed sand that overlies the Ochopee Limestone has been mapped in the study area (Fig. 9). The stratigraphic relation to existing Pliocene-Pleistocene units, such as the Pinecrest Member of the Tamiami Formation, has not been resolved. Future analysis of mollusks could help to clarify relations, but Scott and Wingard (1995) have discussed the problems associated with biostratigraphy and lithostratigraphy of the Plio-Pleistocene in southern Florida.

Three lithofacies have been identified within the unnamed sand for an area shown in Figure 1: (1) a quartz sand facies, (2) a pelecypod lime rudstone and floatstone facies, and (3) a terrigenous mudstone facies (Table 7). The quartz sand facies is characteristic of most of the unnamed sand.

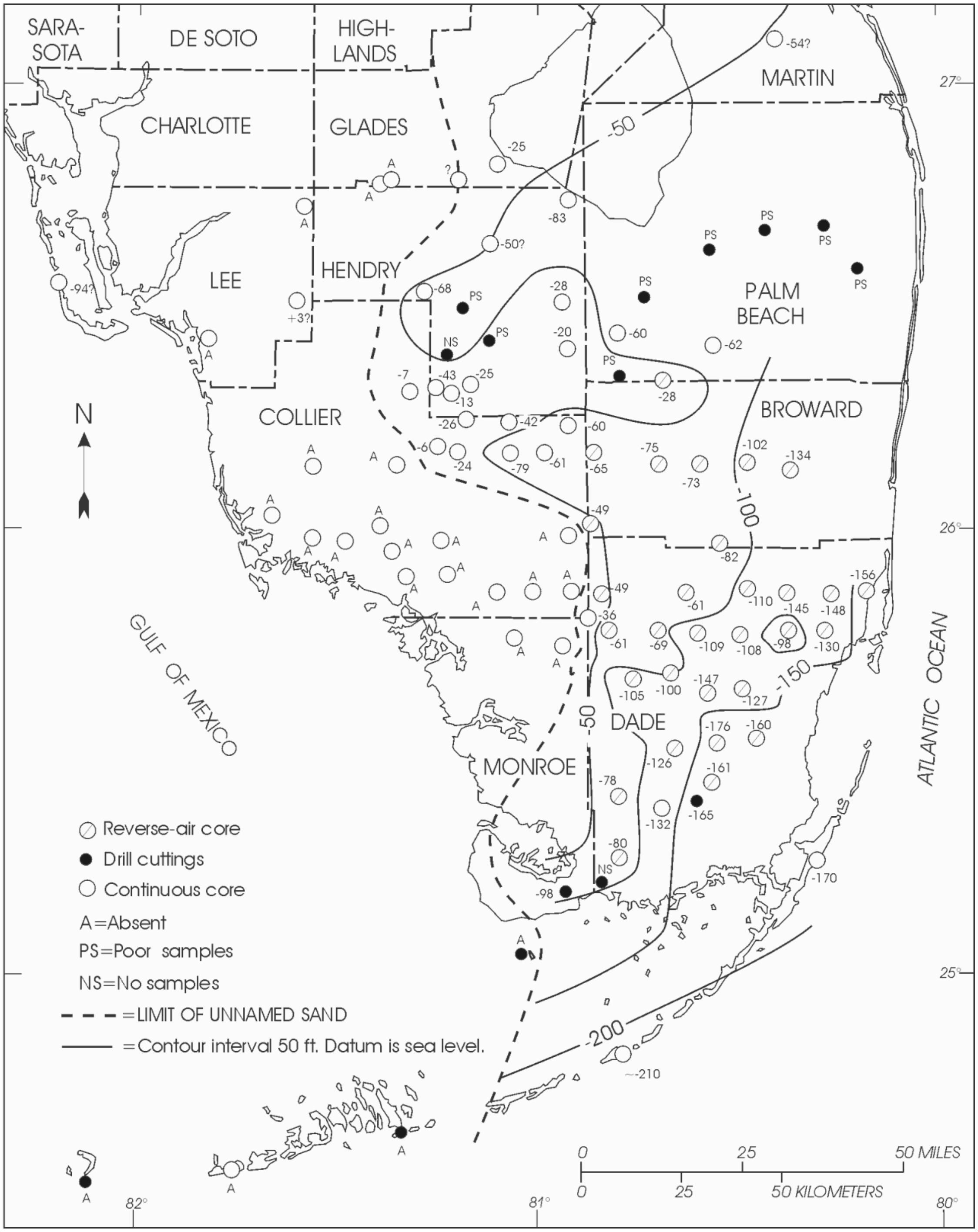

Figure 9. Structure contour map of an unnamed sand that overlies the Ochopee Limestone Member of the Tamiami Formation. Structure contours show altitude in feet below sea level of base of the Pinecrest Sand.

Table 7. Lithofacies characteristics of the unnamed sand for the area outlined in Figure 1

[Visual estimation was made for porosity. Hydraulic conductivity was estimated by comparison of corehole from Fish and Stewart (1991, table 6)]

Characteristic	Lithologic description
Quartz Sand Facies	
Depositional textures	Quartz sand with locally abundant fossils
Color	Mainly yellowish-gray 5Y 8/1 and yellowish-gray 5Y 7/2; locally medium-gray N5 to very light gray N8, very pale orange 10yR 8/2, light-olive-gray 5Y 6/1, light-olive-gray 5Y 5/2, grayish-yellow 5Y 8/4, grayish-orange 10YR 7/4, and dark-yellowish-orange 10 YR 6/6
Grain size	Mainly very fine to fine quartz sand; ranges from silt to very coarse quartz sand; carbonate grains range from silt to pebble size
Carbonate grains	Pelecypods (local oysters), undifferentiated skeletal fragments, echinoids, serpulids, bryozoans, and benthic and planktic foraminifers
Accessory grains	Trace to 3 percent phosphate and heavy mineral grains; local trace mica; local minor terrigenous clay
Porosity	Mainly intergrain and local intragrain, ranges from 5 to 25 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
Pelecypod Lime Rudstone and Floatstone Facies	
Depositional textures	Pelecypod lime rudstone or floatstone with quartz sand-rich lime packstone and grainstone matrix
Color	Yellowish-gray 5Y 8/1, medium-gray N5 to light-gray N7, very pale orange10yR 8/2, pale-yellowish-brown 10yR 6/2
Grain size	Carbonate grains up to pebble size; quartz sand mainly very fine to fine and ranges from silt to coarse size
Carbonate grains	Pelecypods, undifferentiated skeletal fragments, gastropods, oysters, serpulids, bryozoans, cerithiids, and echinoids
Accessory grains	Trace to 3 percent phosphate and heavy mineral grains
Porosity	Mainly intergrain and moldic; local intragrain and shelter; ranges from 5 to 15 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
Terrigenous Mudstone Facies	
Depositional textures	Silty terrigenous mudstone to quartz sand-rich terrigenous mudstone; locally grades into terrigenous clay-rich lime mudstone
Color	Light-olive-gray 5Y 5/2, light-olive-gray 5Y 6/1 and yellowish-gray 5Y 8/1 ; locally pale-olive 10y 6/2, light-olive-gray 5Y 6/1, dusky-yellow-green 5GY 5/2, and yellowish-gray 5Y 7/2
Grain size	Mainly terrigenous clay; quartz grains range from silt to fine sand size; local medium to coarse quartz sand
Carbonate grains	Pelecypods (local oysters), benthic and planktic foraminifers, undifferentiated skeletal fragments, and fish scales
Accessory grains	Locally common quartz grains; trace to 1 percent phosphate grains; trace to 3 percent heavy mineral grains; local trace mica; trace plagioclase and microcline
Porosity	Intergrain; less than or equal to 5 percent
Hydraulic conductivity	Very low (less than 0.1 foot per day)

The terrigenous mudstone facies occurs mainly in the north-central part of the study area outlined in Figure 1 where the facies typically occurs as one or two units within the lower part of the unnamed sand. The pelecypod lime rudstone is found only locally as discrete beds within or near the top of the unnamed sand. Figure 6 shows that the unnamed sand is probably equivalent to much of Interval II and all of Interval III defined by Guertin et al. (1999) within the Long Key Formation.

The unnamed sand ranges from 20 to 60 feet in thickness in most of the study area. The unnamed sand is thickest (about 120 feet) in central and south-central Miami-Dade County. A structure contour map of the base of the unnamed sand (Fig. 9) shows that the unit pinches out in the western portion of the Florida peninsula. In southern Miami-Dade County, the unnamed sand merges with siliciclastics of the Long Key Formation as defined by Cunningham et al. (1998) in the Florida Keys. The structure contour map at the base of the unnamed sand and the cross sections shown in Figures 5 and 6 indicate that quartz sands of the unnamed sand were transported southward mostly along the southeastern coast of Florida to the Long Key Formation in the Florida Keys.

Sequence Stratigraphy

The sequence stratigraphy of the unnamed sand is more poorly defined than that of the Ochopee Limestone and Peace River Formation. The unconformity and sequence boundary at the top of the Ochopee Formation defines the base of the unnamed sand. Possibly a subaerial unconformity at the base of the Pleistocene defined by Perkins (1977) bounds the top of the unnamed sand. The unnamed sand is correlated to the middle and upper parts of Intervals II and all of Interval III defined by Guertin et al. (1999) within the Long Key Formation (Fig. 6), suggesting assignment to the early and late Pliocene. For the present study, however, assignment of the Ochopee Limestone to Sub-zone CN12aA, at least in part, suggests that the unnamed sand has a late Pliocene age (Fig. 7).

Micropaleontology

One sample from the terrigenous mudstone lithofacies of the unnamed sand from the PB-1703 corehole in Palm Beach County was examined (Fig. 1 and Table 4). The assemblage present is consistent with deposition on a marine shelf (Tables 4 and 5).

SUMMARY OF DEPOSITIONAL TIMING

Peace River Formation

Established chronologic data (Cunningham et al., 1998; Edwards et al., 1998; Guertin et al., 1999; Missimer, 1999; Weedman et al., 1999) and the new biochronology of this study indicate that the Tortonian and Zanclean ages bracket deposition of the Peace River Formation. These chronologic data allow constraints to be placed on the ages of DS1, DS2, and DS3. In southwestern Florida, Missimer (1999) divided the Peace River Formation into one supersequence (lower Peace River Formation) and one depositional sequence (upper Peace River Formation). Deposition of the lower Peace River Formation of Missimer (1999) occurred between the intervals of 11 and 8.5 Ma (Tortonian age) and deposition of the upper Peace River Formation of Missimer (1999) was between 5.2 and 4.3 Ma (Zanclean age).

Biostratigraphic results presented herein indicate that terrigenous mudstones from the base of DS1 of the Peace River Formation in Palm Beach County probably can be assigned to Zone CN8

(Tortonian age). The boundaries of Zone CN8 are 9.4 and 8.6 Ma (Fig. 7). Micropaleontologic results show that deposition of CS2 of the Peace River Formation occurred from late Tortonian and Messinian age. Micropaleontologic results also suggest that CS2 is, at most, 7.2 Ma and likely no younger than 5.6 Ma; however, results from Cunningham et al. (1999) suggest an age ranging between 7.44 and 6.83 Ma.

Missimer (1999) reports a hiatus in deposition of the Peace River Formation between 8.5 and about 5.2 Ma in southwestern Florida--an interval in time that brackets deposition of CS2 in southeastern Florida. Edwards et al. (1998) indicate that the unnamed formation in western Collier County, which is equivalent to the Peace River Formation for the present study, ranges in age from 9.5 to 5.7 Ma based on strontium-isotope chemostratigraphy, but biostratigraphic data suggest it may be as young as Pliocene. Weedman et al. (1999) produced similar results for the Peace River Formation and unnamed formation in eastern Collier and northern Monroe Counties, which are equivalent to the Peace River Formation for the study herein. Weedman et al. (1999) report a late Miocene age for the Peace River Formation based on dinocysts and strontium-isotope chemostratigraphy, and an age for the unnamed formation ranging between 6.9 and 4.6 Ma (late Miocene to Pliocene) based on strontium-isotope chemostratigraphy. Coccolith data from the condensed section of DS3 and the age of overlying mudstones in well W-9104 constrain the age of DS3 to range from 5.23 to 3.83 Ma.

Depositional sequence 1 (DS1) correlates to the lower Peace River Formation of Missimer (1997; 1999) where the data from the present study are linked to data from Missimer at the W- 17115 corehole (Figs. 5 and 7). Data presented by Edwards et al. (1998) and Weedman et al. (1999) are consistent with deposition of DS1 during the Tortonian and Messinian ages (11.2-5.32 Ma). Results herein suggest that the age of DS1 is probably at most 11 Ma and no younger than 7.2 Ma, the probable maximum age of CS2. Biostratigraphic data from CS2 and CS3 are consistent with deposition of DS2 during the latest Tortonian and Messinian ages (Fig. 7). Interval I of the Long Key Formation in the Florida Keys (Guertin et al., 1999) is probably equivalent to DS2 (Fig. 7). Guertin et al. (1999) assign Interval I to the Messinian age, suggesting that Interval I may be equivalent to the upper portion of DS2 that occurs beneath the Florida peninsula (Fig. 7). Deposition of the upper Peace River Formation of Missimer (1999) in southwestern Florida may be coincident with DS3 in southeastern Florida as suggested by an early Pliocene age for the upper Peace River Formation (Fig. 7).

Ochopee Limestone Member of the Tamiami Formation

Results presented herein suggest that the Ochopee Limestone or DS3 was deposited during a time spanning the early-late Pliocene boundary and during the eustatic cycle TB3.6 of Haq et al. (1988) as shown in Figure 6. Coccolith data from the base of DS4 in well W-9104 are consistent with assignment to Sub zone CN12aA (3.83-3.62 Ma) as shown in Figures 5 and 6. Cunningham et al. (2000, in press) used silicoflagellate and coccolith data to determine the age of the lower boundary of the Tamiami Formation to be near the early-late Pliocene boundary in the W-18074 and W-18075 coreholes in Glades County (Fig. 1). Cunningham et al. (2000, in press) also show a regional-scale seismic sequence boundary at the contact between the Peace River Formation and the Tamiami Formation. The Tamiami ages at well W-9104 and the two coreholes (W-18074 and W-18075) in Glades County are consistent with determination by Missimer (1999) that deposition of the Tamiami Formation began about 0.2 million years after the Peace River Formation at 4.3 Ma or Tamiami deposition began at about 4.1 Ma. Edwards et al. (1998) and Weedman et al. (1999) determined the Ochopee Limestone was most likely deposited during the early Pliocene, but the margin of error spans the late Miocene to late Pliocene age. A distinctive molluscan assemblage in several coreholes indicates an age for the Ochopee Limestone near the early-late Pliocene boundary (Edwards et al., 1988).

Age determinations of Edwards et al. (1998), Weedman et al. (1999), and Missimer (1999), and correlations for the present study suggest that deposition of the Ochopee Limestone was coincident with deposition of the lower portion of Interval II of the Long Key Formation (Fig. 6). Foraminiferal sandstone beds occurring at the base of Interval II are composed of a lithofacies characteristic of the Stock Island Formation (Cunningham et al., 1998), and may represent a distal portion of the Ochopee Limestone ramp (Fig. 6).

Unnamed Sand

The unnamed sand was probably deposited during the late Pliocene based on age determinations for DS4 (Fig. 6). Correlations shown in Figure 6 suggest that the unnamed sand is coincident with deposition of the middle and upper parts of Interval II and all of Interval III (Guertin et al., 1999) within the Long Key Formation

CONCLUSIONS

In southern Florida, a late-early to early-late Pliocene carbonate ramp (Ochopee limestone Member of the Tamiami Formation) is sandwiched between underlying marine siliciclastics of the late Miocene-to-early Pliocene Peace River Formation and an overlying late Pliocene unnamed sand. The Peace River Formation contains at least three depositional sequences (DS1, DS2, and DS3), and the Ochopee Limestone forms a fourth depositional sequence (DS4). The two youngest depositional sequences of the Peace River Formation, DS2 and DS3, contain condensed sections composed of terrigenous mudstone typically overlying diatomaceous mudstone. A maximum flooding surface is interpreted to coincide with the contact between diatomaceous mudstone and terrigenous mudstone. The maximum flooding surface bounds the transgressive and highstand systems tracts of DS2 and DS3. The condensed sections have yielded abundant microfossils, which contribute to their importance for biochronology, defining and correlating the sequences, and reconstructing depositional environments.

Established chronologies and new micropaleontologic results indicate that the Tortonian and Zanclean ages bracket deposition of the Peace River Formation and provide constraints on the timing of the deposition of the three Peace River depositional sequences. Depositional sequence (DS1) prograded across the present-day southern peninsular portion of the Florida Platform during the Tortonian age and laps out near the southern margin of the peninsula. The age of DS1 is probably at most 11 Ma and no younger than 7.2 Ma. During the latest Tortonian and Messinian ages (probably between 7.2 and 5.6 Ma), progradation of DS2 overstepped the southern lap out of DS1 and extended at least as far as the Florida Keys. Deposition of DS2 siliciclastics ended, at the latest, near the Miocene-Pliocene boundary.

Presence of DS3 in southeastern Florida and possibly southwestern Florida and absence in southernmost Florida suggest a reduction in the southward supply of quartz sand during deposition of the sequence (between 5.23 and 3.83 Ma). This reduction in supply of siliciclastics to southernmost Florida was followed by aggradational accumulation of heterozoan temperate carbonate sediments of the Ochopee limestone. Deposition of the Ochopee limestone ended with basinward lap out near the southern margin of the present-day Florida peninsula. The lap out is probably coincident with the edge of the siliciclastic shelf containing DS2 of the Peace River

Formation. Deposition of the Ochopee limestone probably occurred during a late-early to early-late Pliocene transgressive to high-stand sea-level conditions during eustatic cycle TB3.6 of Haq et al. (1988). Increased supply of siliciclastics to southern Florida resumed in late Pliocene, burying the Ochopee limestone ramp. These siliciclastics extend as far south as the middle and northern Florida Keys. The unnamed sand includes these siliciclastics, which probably are coincident with middle to upper quartz sands of the Long Key Formation beneath the Florida Keys. Southward transport of quartz sands of the unnamed sand was mostly along the eastern coast of Florida.

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